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EXPERIENCE IN ANALYZING INFRARED PICTURES OF CLOUDS OBTAINED BY THE METEOROLOGICAL SATELLITE "NIMBUS-1"

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At present, the availability of artificial earth satellites has made it possible to investigate meteorological processes on a planetary scale. In particular, observing the distribution of clouds over the earth is of great interest, inasmuch as clouds constitute a highly important element in the weather and location and movements of atmospheric formations can be judged by their spatial distribution.

During daylight hours, clouds can be detected by ordinary television cameras, but at night, however, it is necessary to employ special, highly-sensitive television cameras or an infrared direction-finding method (measurement of heat radiation).

It is most advantageous to measure radiation in those regions of the spectrum where the distorting effects of the atmosphere are small and, at the same time, the radiation from the earth and clouds is sufficiently intense. These conditions are satisfied by the so-called "windows of transparency" of the atmosphere, in the wavelength region about 4 microns and in the 8 to 12 micron spectral range in which outgoing radiation is usually measured.

Since the temperatures in the atmosphere usually decrease with altitude, clouds generally have temperatures lower than the temperature at the ground surface, and their radiation is correspondingly less intense.

In order to observe clouds at night, the American meteorological satellite "Nimbus-1" is equipped with infrared apparatus (IK). The infrared apparatus operates on the principle of measuring the outgoing radiation from the earth-atmosphere system within the 3.7 and 4.2-micron region of the spectrum.

The authors present in this article the results from a comparative analysis of ordinary meteorological data and the data on clouds obtained from the satellite "Nimbus-1" with the aid of infrared apparatus and represented by two infrared negatives obtained at midnight on 2 and 6 September 1964 over the territory of the Soviet Union.

Every type of surface is distinguished in the photographs by unique brightness, depending on the amount of heat energy radiated by that surface. The warmer the surface, the more energy it radiates (other conditions being equal) and the darker it appears in the negative.

Cloud formations, whose upper boundaries are colder than open areas over land and water surfaces, appear in the photographs as white spots and bands of various brightness. The brightest spots and bands correspond to clouds which have reached maximum heights and whose upper boundaries have the lowest temperatures. The less bright sections of the pictures correspond to clouds with higher temperatures on their upper boundaries, also to thin clouds in the upper and middle layers, and to broken cloud masses (the radiation from these formations is mixed with radiation from the underlying ground surface.

Ice-covered surfaces differ from clouds by a less light (gray) tone in the pictures and by sharply defined boundaries.

The pictures of the ground surface have a dark gray, microstructured appearance and show various details due to temperature inhomogeneities. In a number of instances, low-lying areas differ in tone in the picture from areas which are higher above sea level.

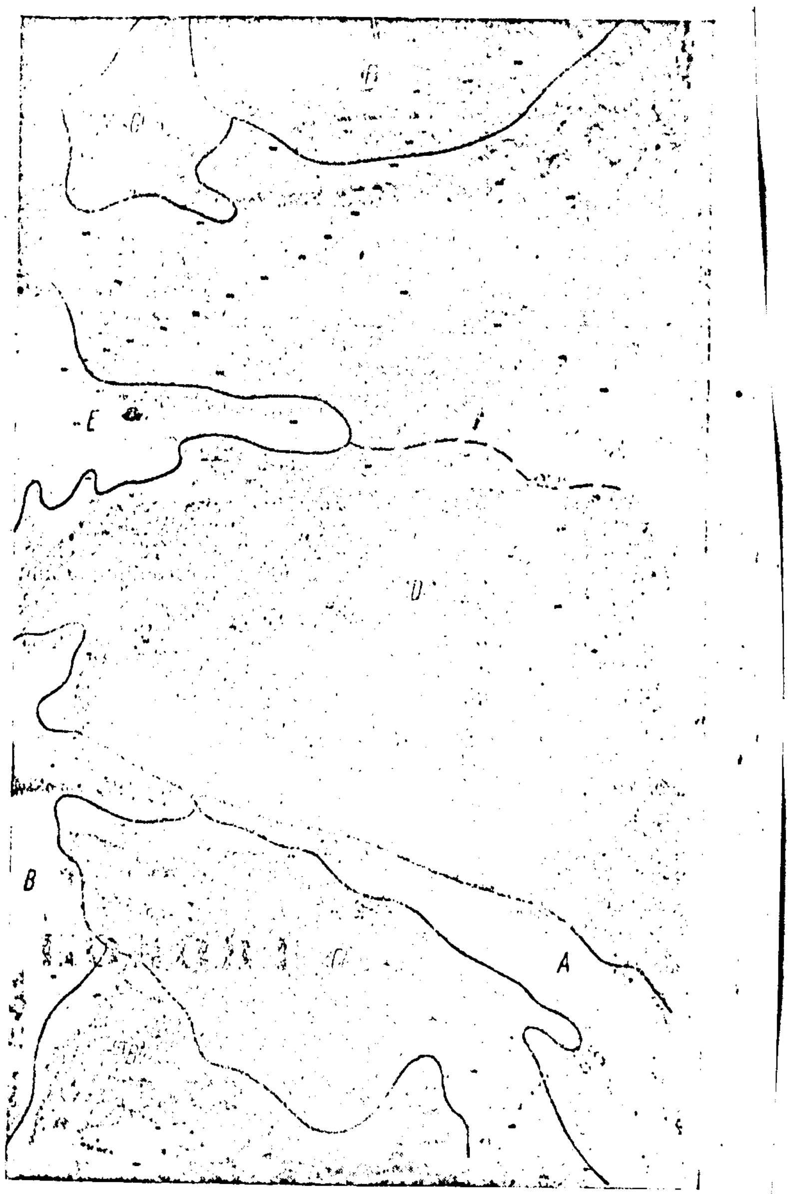

Fig. 1. Infrared picture of clouds obtained from the artificial earth satellite "Nimbus-1" on 6 September 1964.

Water surfaces, which have higher temperatures during the night and have more homogeneous temperature distributions over their area, are distinguished in the pictures by a darker, more homogeneous tone. Due to the high homogeneity of pictures of water surfaces, the shore lines of seas, also the outlines of lakes and large rivers are clearly visible in the photographs.

The analysis of these two infrared photographs consisted of their decoding and a comparison of the pictures of clouds and the ground surface with data from ordinary ground meteorological observations and the synoptical situation, which involved the use of weather maps, constant pressure maps, cloud analysis maps from ground and satellite data, values of the radiation balance computed for a number of points (from actinometric observation data), and emagrams which were used for determining the temperatures and heights of the upper boundaries of clouds.

Figure 1 shows one of these infrared photographs with a picture of the cloud cover over Western Siberia obtained 6 September 1964 at 0030 hours local time (for the meridian 75^{o}E).

The infrared picture includes a zone about 1300 kilometers wide east of the Urals which extends from the virgin lands region and the southern Urals (lower part of the photograph) to the Sea of Laptyev (upper right corner of the photograph). A transformed geographical coordinate grid is imposed on the photograph.

The nature of the weather over the photographed territory is determined by a large cyclone with its center over the northern Urals and an anticyclone located over the Central Siberian Plateau.

Masses of cold, unstable air arrived at the rear of this cyclone from the direction of the Urals at the time the photograph was taken. Waves appeared on the cold front connected with this cyclone, passing from its center toward the southeast, almost parallel to the upper reaches of the Ob'River, to the Kuznetskiy Alatau Range, while a separate cyclone formed east of Novosibirsk with a weakly outlined crest at its rear. The warm front of this cyclone passed over the extreme northern regions of Siberia.

Several gradations of brightness are clearly distinguishable in this photograph, ranging from a bright white tone to a dark tone.

A bright white band which corresponds to a ridge of high, cold clouds is clearly visible in the lower part of the photograph (a). The brightness of the picture of the clouds along the band is not uniform; the clouds in the right part of the band are brightest and the brightness of the strip decreases to a gray level in the left part. These clouds are connected with a cold front; at the same time, rain and storms were observed in places in that section of the front corresponding to brighter clouds, which is evidence of the great vertical extent of these clouds. The cloudiness of the section of the front with lower brightness of the picture is less well developed and is primarily due to stratocumulus clouds. The trough of the cyclone in which this front is located is a low-pressure formation traced down only to the 850-millibar level.

To the left, in the lower part of the photograph (BB'), can be seen quite marked cloudiness connected with a second cold front, with rains observed in some places. This front passes along the meridian 70°E, from Salekhard to Tselinograd. One can see between these cloud masses a section with a light gray tone (C) which corresponds to a region with clear weather in the rear of the cold front.

The middle part of the photograph (D) is distinguished by the darkest tone and corresponds to the warm sector of the cyclone with clear weather due to the influence of the anticyclone located above the Central Siberian Plateau. This anticyclone is a high-pressure formation with an almost vertical spatial axis; the anticyclone is traced down to the level of the tropopause.

A fairly large mass of dense cloudiness (E) which extends to the right can be seen in the left part of the photograph (about 75 to 80° N). This cloud mass is connected with the forward part of the cyclone and a warm front. The clouds in this system are marked by greater brightness only in the extreme left part of the photograph corresponding directly to the forward part of the cyclone. The entire remaining mass of cloudiness of the warm front is shown by a gray, at times light, tone in the picture.

An analysis of ground observations and vertical temperature sounding shows that the cloud system of the warm front is actually well developed only in the forward part of the cyclone where the upward movement of air is distinguished by high intensity. Here the cloud system contains stratonimbus clouds which are the source of continuous precipitation. The cloud system of the warm front distant from the center of the cyclone is of low density.

Bands of less bright white and gray tones are clearly visible in the upper part of the picture (F) which form a vertical pattern. The direction of the cloud bands in the vicinity of this pattern almost coincide with the direction of the wind and the center of the cyclone on the 300 millibar level (an anticyclone is located at the ground surface in this vicinity).

The dark spots in the left upper corner of the photograph (G) are apparently areas of open water among ice formations in the Arctic Ocean (according to data from air reconnaissance, open water areas were observed from 9 to 10 September in the vicinity of the Cevernaya Zemlya Archipelago).

It was established from analysis of the emagrams that the height of the upper boundaries of the clouds in the areas denoted by the letters B and B' is within limits of 3.5 to 4.0 kilometers, and the temperature of the clouds at this height is -10 or -15° C. In the vicinity of Perm' and northwest of Sverdlovsk, also in the area denoted by the letter A, one can consider that the height of the clouds is 10 to 11 kilometers and their temperature, at this height, is about -50°.

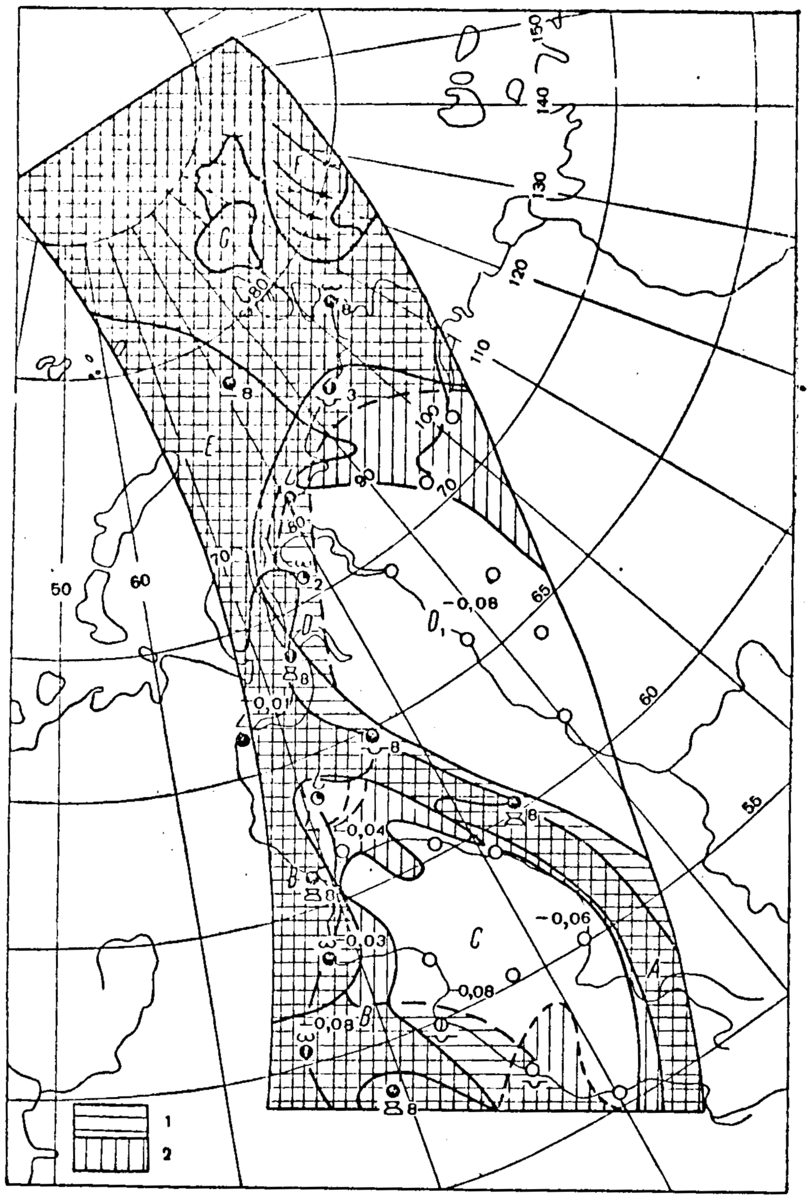

Fig. 2. A schematic map of the distribution of clouds by ground data (1) and by data obtained from the artificial earth satellite "Nimbus-1" (2) at 0030 hour (local time) on 6 September 1964.

Figure 2 shows, for purpose of comparison, data on the distribution of clouds obtained from the satellite and from ground observations at 0000 hour, local time, on 6 September 1964.

It can be seen in the figure that the zones of cloudiness indicated by ground and satellite data coincide. However, there are individual discrepancies which can be explained either by difficulties in observing clouds from the ground surface at night, or by inaccurate geographical coordination of satellite data.

As can be seen in Figure 1, area D with clear weather (the area of the Yenisey River Basin) shows a darker tone than area C, which is also clear, according to data from meteorological stations.

This discrepancy in tones produced by two cloudless areas can be explained by starting with an analysis of aerosynoptical data. The lighter tone of the infrared picture of the southern cloudless zone is explained by the lower temperature in this zone in the ground layer of the atmosphere extending up to a height of about 3 kilometers, which is quite apparent from the data presented in Table 1.

- Table 1 -

TEMPERATURE

Area	At Ground Surface	At the 850 - Millibar Level	At the 700 - Millibar Level
Southern (C)	5 - 6	0 - 2	-5 - -10
Northern (D)	Along rivers 10-15	8 - 10	0 - -2
	In mountains 5-6		

It should also be noted that the high pressure crest caused by cloudless weather in the vicinity C is a low formation which can scarcely be traced to the 850-millibar level. Higher above this area one observes a well defined trend to cyclone formation which can lead to the appearance of rising currents in the upper layers of the troposphere and the formation of thin clouds in the upper layer which are not visible to ground observers at night.

In the north, however, the high pressure crest connected with cloudless weather, as stated previously, can be traced to great heights (an extensive closed region of increased geopotential is observed on the 300 millibar level over this area). Thus, there should be descending currents preventing the formation of clouds over the northern area of cloudless weather.

Values of the radiation balance obtained at ground actinometric stations can be used as additional material for confirming the explanations given here.

Figure 2 shows the values of the radiation balance (in cal/cm^{2}min) at 0030 hours local time, 6 September 1964. It can be seen from an inspection of this figure that the most characteristic values of the balance range from -0.06 to -0.11 cal/cm^{2}min. for cloudless areas (on the average, -0.08 cal/cm^{2}min.) and from -0.01 to -0.04 cal/cm^{2}min. for clouded areas.

As an example, let us consider the observations for cloudiness at Tobol'sk. At 0000 hour, local time, on 6 September 1964, according to data from the weather station, it was clear in the vicinity of Tobol'sk, but at 0030 hours, according to actinometric observation data, there was cloudiness in the upper and middle layers (Cs, As 10 points, with clear gaps). The value of the radiation balance was 0.03 cal/cm^{2}min; this provided grounds for assuming that the weather station observer could not notice thin clouds in the upper layer at night and establish the percentage of cloud cover.

However, one might also assume that clouds could appear over Tobol'sk within 30 minutes (from 0000 hour to 0030 hour). The value of the radiation balance at Tobol'sk also provides grounds for assuming that high, broken clouds could have existed in the upper layer in area C (light gray tone in Figure 1) which would have transmitted heat radiation from the ground surface sufficiently well.

The photograph of 2 September 1964 was taken over the Urals and Western Kazakhstan at midnight local time. The width of the territory along the path of the flight covered by the photograph was also about 1300 kilometers in this case (Figure 3).

The weather in the northern part of the photographed zone was determined by a cyclone located above the northern Urals; a trough with a cold front extended south from this area along the right edge of the zone.

In the southern part of this territory, the weather was determined by a high pressure crest connected with an anticyclone located over western Europe. Masses of cold air behind the cold front extended from the Norwegian and the Barents Seas to the European territories of the USSR. Western Siberia and the eastern areas of Kazakhstan were occupied by masses of warm air which had arrived from central Asia.

When analyzing the photograph, one's attention is attracted by the great variety of brightness and tone, from almost black to bright white.

The three brightest white areas in the photohraph correspond to three cloud systems. The first system, in the upper right part of the photograph, is connected with a cyclone over the western Urals; the second, in the middle right part of the photograph, is connected with the cold front over the middle and southern Urals and the Aral Sea; the third system, in the lower part of the Caspian Sea.

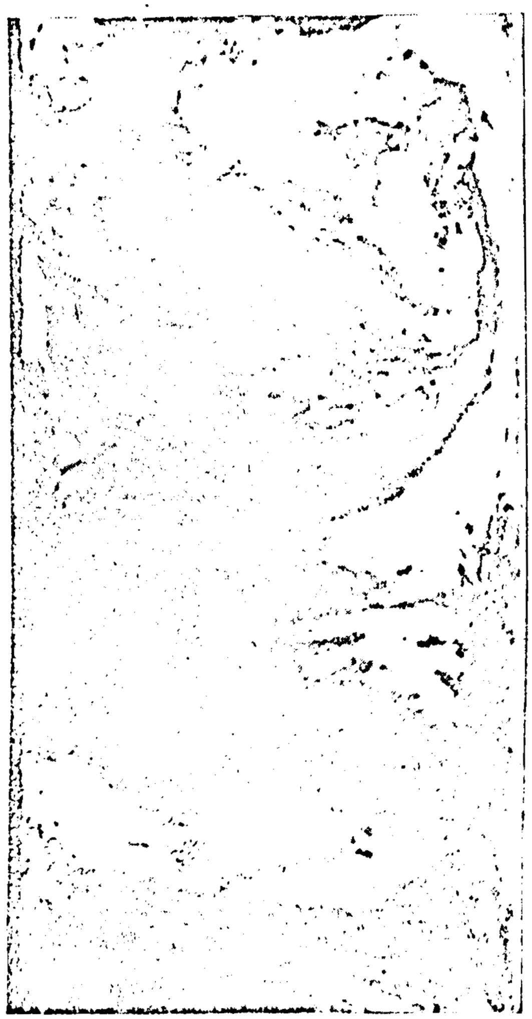

Fig. 3. Infrared picture of clouds obtained from the artificial earth satellite "Nimbus-1" on 2 September 1964.

An analysis of data from ground observations and vertical temperature sounding indicates the existence of a difference in the vertical extent of the clouds and in the temperatures in their upper boundaries. Thus, the clouds in the Caucasus region were up to 2 kilometers thick, the height of the upper boundaries up to 5 kilometers, and the temperature at this height was -5°. In the southern Urals and middle Urals area, the clouds were from

0.2 to 9.5 kilometers thick, the heights of the upper boundary ranged from 5.5 to 10 kilometers, and the temperatures from -12 to -50°. The clouds in the cyclone over the northern Urals were as much as 10 kilometers thick, the height of the upper boundary was 10.5 kilometers, and the temperature on the upper boundary was -58°.

In the photograph, all these clouds showed the same brightness and were homogeneous. This can be explained apparently by the low sensitivity of the apparatus to below zero temperatures.

Slightly clouded and clear weather was noted for the rest of this territory at midnight 2 September, but the tone of this area appearing in the photograph was very inhomogeneous.

The Caspian Sea, and to the left of its southern part, Lake Sevan, are clearly shown in the lower part of the photograph by the dark, homogeneous image of the water surfaces and the characteristic outlines of their shores. The temperature of the water in the Caspian Sea at midnight 2 September ranged from 20 to 24°, and the air temperature in the coastal areas, about 2 to 4° lower.

The outlines of the Kuybyshev Reservoir on the Volga River and, somewhat to the north, the Kamsk Reservoir are shown clearly in the middle left part of the photograph. The rest of the Volga is shown far less clearly since its width is considerably less than the resolution of the apparatus, even though the temperature of its water exceeded the air temperatures at neighboring weather stations by 6 to 9°.

The tone of the picture of the underlying surface in the middle Volga area was brighter than the tone of the picture of the lower Volga area. This difference in the tones of the pictures of two neighboring areas was due to the lower air temperatures in the central Volga area (4 to 5° lower), differences in the nature of the soil and vegetation, and in the altitude above sea level. In addition, dissipating altocumulus clouds (up to 2 to 4 points) still remained in the middle Volga area which could merge with the background and increase the brightness of the picture somewhat.

The deserts and semi-deserts (the territory to the east of the Caspian Sea and its northern shores) also showed brighter in the picture than the lower Volga area in spite of the higher air temperatures here. This was most probably caused by a difference in the underlying surface.

The snow-covered El'brus Mountains are clearly visible in the lower part of the photograph.

This analysis of satellite data on clouds showed that the principal difficulties which appear in interpreting the nature of the clouds from the photographs are connected, in the first instance, with the fact that the clouds are represented in the photographs by comparatively large details. The small details, which are characteristic, for example, of cumulus clouds are smoothed over in the photographs. This is because the quality of reproduction of fine details is essentially determined by the resolution of the apparatus. The latter does not provide any information on each resolved element other than the heat radiation averaged over its area. As a result, a single fine detail which does not completely cover a resolved element but has a temperature differing from that of the surrounding background will be registered on the photograph by changed brightness of the entire resolved element, that is, brightness corresponding to the averaged radiation for the entire resolved element.

With the maximum resolution possessed by infrared apparatus at present, the horizontal dimensions of individual elements of cumulus clouds (from several tens and hundreds of meters to 1 or 2 kilometers and more) are too small to be distinguished on the photographs. If the elements of cumulus clouds do not form accumulations of different density and are more or less uniformly distributed over the area, then they will at best create an homogeneous image of decreased brightness on the photograph. On the other hand, scattered clouds will blend with the background without interrupting the picture of the underlying surface.

Moreover, when inspecting the photographs, it is at times very difficult to judge differences in the brightness of the image of continuous cloud masses located at different heights and having quite different temperatures in their upper surfaces. Differences in values of the brightness are not noted apparently on account of the low contrast sensitivity of the apparatus when temperatures are below zero -- which are the temperatures usually observed in the upper boundaries of such clouds. The fact that the human eye is less sensitive to changes in brightness when the brightness values are high, such as those characteristic of high cloud formation, also plays a definite role here.

The work which was performed permits one to draw the following conclusions, which are naturally (due to the very restricted material) as yet only provisional:

1. An infrared picture obtained from a satellite yields a more complete and integrated picture of the distribution of clouds than a synoptic map.

Even in an area with a dense network of meteorological stations, the photographs which were obtained permit one to obtain a more precise idea of the distribution of clouds over large areas of the earth's surface. However, many details of the cloud pattern which are clearly visible in television photographs are smoothed out in infrared photographs.

2. In a number of cases, data on the radiation balance can be used to improve some aspects when interpreting satellite observations.

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